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Spatial Configuration and Density

How Building Density Affects Spatial Arrangement of a Neighbourhood

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Abstract: A large body of research has focused on the various social, environmental and economic ways in which urban density might affect cities. When considering density as one of the elements of urban form, the measurements that studies usually apply, such as net or gross building density, do not have any link to the design of the built form. This paper argues that the same building density can yield different design layouts, thereby emphasising the need for developing other measurements of density in close relationship with design factors. To demonstrate this, several cases with various ranges of density (low, medium and high) were explored through spatial analysis and categorised in three clusters for further study with statistical tests. The results confirm meaningful differences between cases with the same density but different spatial design characteristics. The outcomes also indicate that the category of the cases based on conventional density measures, namely population density and building density (which are commonly used in urban studies), fail to capture design differences when density ranges differ. These results should draw attention to this phenomenon, which appears worthy of further investigation in future studies.

1. INTRODUCTION

Current sustainable urban strategies, in various parts of the world, favour making cities more compact to respond to rapid urbanisation (Hernandez-Palacio, 2017). Although speedy urbanisation has caused many problems for cities regarding accommodating and managing population distribution (Gao et al., 2019), making cities more compact is mainly an attempt to find a more environmentally sustainable urban form. Many studies have focused on the various impacts of high-density urban development in urban planning and design research (Raman, 2010; Hernandez-Palacio, 2017; Kyttä & Broberg, 2014; Dempsey, Nicola, Brown, & Bramley, 2012; Laatikainen et al., 2015), but the measurements they employ to capture density are rarely consistent.

Density in the urban realm can be defined in many ways. The measurement of urban density is usually equivalent to the number of dwellings or the population per unit area. Nevertheless, average density does not represent the variation in urban form and in other characteristics of the aggregated area, such as transport services or land use patterns (Neuman, 2005). The same density range can occur for very different morphologies; thus, planners and designers tend to use a more practical measurement for density that is informative of design configuration. This study therefore attempts to understand if density can impact the spatial arrangement of a neighbourhood through exploring the interaction of spatial design factors with changes in density. This paper uses spatial network analysis to study the street networks of several suburbs selected from three ranges of density: low, medium and high. These cases were also situated in three different areas of the city: inner, middle and outer areas. The study utilised different categorisations and clustering of the cases. Spatial analysis using the space syntax method (Hillier & Hanson, 1984) was conducted on each case to extract its spatial design factor, and ANOVA and t-tests were conducted to explore if the cases and clusters were meaningfully different from each other in terms of their spatial design factors.

1.1 Density in relation to design

Density is an important element of urban form (Hernandez-Palacio, 2017; Dempsey, N et al., 2010). In urban studies, density has become a complex concept defined in many different ways through a wide variety of perspectives, ranging from more commonly used physical forms of density to non-physical aspects like perceived density (Ng, 2014). Measurements of physical density can be broadly divided into two categories: population density and building density. Population density is expressed as the number of people or households per given area, whereas building density is defined as the ratio of building structures to an area unit (Ng, 2014).

Grosvenor and O'NEILL (2014) believe that commonly used density measurements do not accurately capture the structure of the built form, instead ignoring differences in accessibility and location. Another problem with using such measurements for density is that it dismisses the spatial features of the given area, which are important indicators of built density.

Although conventional density measures are widely applied in urban research and practice, several recent studies have attempted to either define density related to the morphological features of the built form or to combine more indicators to define density. That is, instead of using an abstract number to represent density, planners and designers could refer to a measurement that is more indicative of the specific design typologies of a scale.

Hamaina, Leduc, and Moreau (2014) employed a combined measure to address a broader definition of density based on building footprint. They modified the traditional indicators floor space index (FSI) and ground space index (GSI, or compactness) to define the morphological plot and link to neighbourhood function, presenting a classification for density. Another approach based on a combination of plot indicators is the Spacemate matrix introduced by Berghauser Pont and Haupt (2007). In this approach, to describe the compactness of an area, FSI is combined with three other variables – GSI, open space ratio (OSR, or pressure on non-built space) and height (H) – to create a more effective index to show the distribution of density. In addition to these four variables, Pont et al. suggest that a 'density network' should be counted as well. Based on these five variables, Spacemate provides a comparative platform that illustrates the range of intensity and compactness, and the network density of various cases.

Apart from the various density types, Peponis et al. (2007) discuss a type of density related to the physical presence of streets. They argue that the street network maintains a long-lasting framework that directs the redevelopment of land uses and properties. Thus, Peponis et al. investigated how street density is associated with other types of density, including building, population and parcel density. They found a strong association between the density of the street network and both parcel density and population density. In their study, the relationship with building density was subject to the aggregation of land uses; when a unified residential land use existed, the relationship with street density was strong, whereas in cases of mixed land use with non-residential use, the relationship was not strong. This is because the area covered by non-residential buildings often does not follow street morphology, which also raises questions concerning the utility of such measurements in targeting design (Peponis et al., 2007).

Other studies exploring density in relation to design factors have employed spatial analysis. One such method is place syntax analysis, which focuses on geographical accessibility by adding attraction points to the spatial analysis, targeting building density. Ståhle, Marcus, and Karlström (2005) argue that the problem with conventional density measurements is that they assume an equal distribution of density and thus an equal distribution of the attraction points, which discards the important role of attraction points in accessibility analysis.

Defining density measurements related to the morphological properties of street layout and built form is therefore feasible to investigate via network analysis methods. The following section explains the logic behind spatial analysis, which was chosen as the primary method for this paper to better understand the similarities and differences between design characteristics within various density ranges.

1.2 Spatial network analysis

To quantify the network structure of the urban form, mathematical measurements are applied. Most methods employ graph theory to model the urban structure into a more abstract graph consisting of nodes and edges, which streamlines its measurement and interpretation. Using centrality, graph theory can identify the most important nodes in a network (Newman, 2010). One of the primary methods in this approach is space syntax analysis (Hillier, 1996, 1999).

Space syntax is a theory and method used to mathematically represent the spatial configuration of a building or urban area. It has inherently established its fundamental theories based on people's observation, perception and behaviour in responding to their surrounding built form.

In space syntax analysis, the graph represents configurational relations where spatial elements are nodes connected to each other through lines that denote relationships (*Figure 1*).

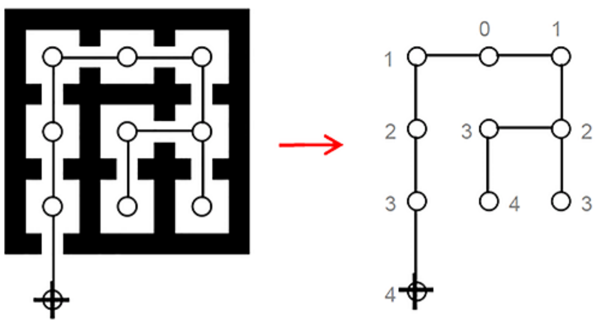

Figure 1. Graph representation of space syntax
(otp.spacesyntax.net)

Spatial relations in space syntax analysis are based on the approach that is taken when measuring the distance between the spatial elements of a network. To measure the distances in a network of disaggregated lines, space syntax defines three distances according to the relationships between adjacent segments: (1) metric distance, or 'shortest length', which measures the Euclidean distance between the two spatial elements; (2) topological distance, or 'fewest turns', which is the number of turns (changes in direction) necessary to reach a destination; and (3) angular distance, which indicates the angular changes that occur when travelling between two points on a graph (Hillier & Iida, 2005). Based on the definition of angular distance, space syntax analysis measures various spatial variables, including depth, integration, choice and connectivity.

Depth index is measured as the shortest distance between the spatial elements, whether metric, angular or topological, based on how it is abstracted in human navigation. This is related to the definition of the connectivity parameter, which denotes the number of immediate neighbours of each node. These two parameters are defined in the following equation:

$$\sum_{s=1}^{m} a * Ns = \begin{cases} connectivity\ iff\ m = 1 \\ local\ depth\ iff\ m = k \quad 1 < k < \dfrac{l}{local} depth(unite\ k = 3) \\ global\ depth\ iff\ m = 1 \end{cases}$$

Where k is the parameter, s is the operator, l is the shortest distance and Ns is the number of nodes with the shortest distance.

The integration value can calculate the closeness and accessibility of a point in a graph in relation to the other surrounding spaces. Integration is similar to closeness in centrality measurements, but integration calculates the angular distance whereas closeness takes metric distance into account. This value can predict the number of people present in a given area (Penn et al., 1998). The integration value is calculated via the following formula:

$$C_c(P_i) = \frac{1}{\sum_k d_{ik}}$$

Where d_{ik} is the length of a geodesic (shortest path) between node P_i and P_k (Hillier & Iida, 2005).

Choice in the space syntax analysis is mathematically similar to betweenness centrality, which refers to the probability of falling on any shortest path that links any pair of segments for a street segment. The following formula defines the value of the betweenness in a network:

$$C_B(P_i) = \sum_j \sum_k g_{jk(P_i)} / g_{jk} \quad (j < k)$$

Where $g_{jk(Pi)}$ is the number of geodesics between nodes P_i and P_k that contain node P_i, and g_{ik} is the number of all geodesics between P_i and P_k.

In this paper, all these measures were included in calculations to quantify the spatial design attributes of each case.

2. METHODOLOGY

This section presents the procedure of the case study in three steps. In the first step, the case selection criteria are presented, as well as the logic behind categorising using a secondary data source. In the second step, the process of data access (cities maps) is illustrated with some examples of the required preparation method as a primary data source. The final step proceeds to clustering the cases based on the research aim and design.

2.1 Case selection and clustering

Cases were selected from four different cities, Edinburgh, Oxford, Glasgow, and Sheffield, based on their density, layout form and location in relation to the city centre. The cases were required to contain a higher density range in the inner area that began to decrease exponentially as distance from the city centre increased, and represent a variety of layout forms, from grid to cul-de-sac. Three cases from each city were chosen from inner, middle and outer areas so that they represented various density ranges, from low to medium to high. The methods used here to categorise and select cases were based on those used in a previous study conducted in the UK (Dempsey, Nicola, Brown, & Bramley, 2012) due to the comprehensive data available from the study and the suitability of the cases for the purpose of this study. To conduct the space syntax analysis, street centreline maps were acquired from the Open Street Map (OSM).

2.2 Clustering of the Cases

To explore if cases were meaningfully different from each other in terms of their spatial design factors, the study only selected those with similar density ranges in the same location category (inner, middle or outer). The only exception to this occurred in Cluster 3, where the density range of the outer neighbourhood in Case B had a density range very similar to the middle range density of the other three cases. Accordingly, eight cases that were more suitable for clustering and the designed tests were selected from the twelve cases (three from each city). These eight cases were divided into three clusters, with each cluster representing a similar density covering different locations and layouts, and three different density ranges (*Table 1*).

Table 1. Overview of neighbourhood cluster test types (1, 2 and 3)

Test	**Clustering**	**Density (p/ha)**	**Location**
1	Two neighbourhoods; one from Case A and one from Case D	27	Outer
		27	
2	Two neighbourhoods; one from Case A and one from Case C	271	Inner

		226	
3	Four neighbourhoods; one from Case A, one from Case B, one from Case C, and one from Case D	70	Middle
		59	Middle
		68	Middle
		63	Outer

2.3 Map Preparation

The data provided by OSM, exported in XML format, were processed in Rhinoceros 3D using a plugin for the Grasshopper 3D named Elk to generate the road centrelines (*Figure 2*).

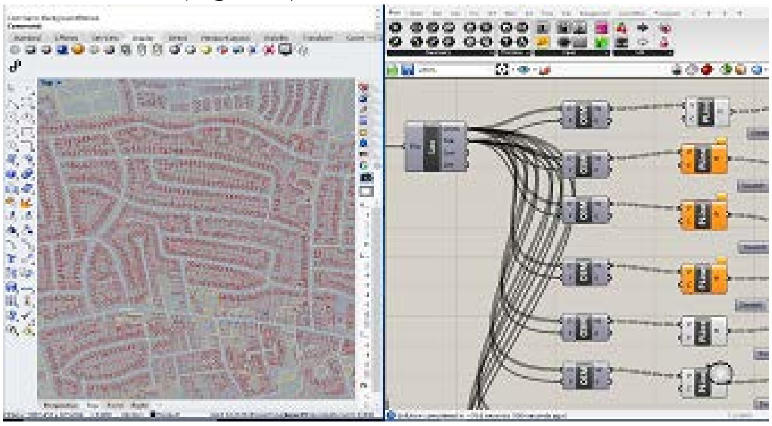

Figure 2. Generation of the plan layouts and road centrelines of the cases using Elk plugin (source: Authors)

Because the British study that this study is modelled upon gathered street data more than 10 years ago, the maps were compared with the historical database available from Google Earth Pro to enable adjustments to the network maps. Despite new developments that have occurred mainly at the building level, the street network remained the same for most cases. There were a few cases with street networks that had been changed, however, and such alterations were applied to the cases' maps manually to remain as close as possible to the actual network identified in 2006. This was achieved by using Google Earth's 3D virtual tours (*Figure 3*) and various street views from different directions. Maps were double-checked to determine if all the road lines in the map actually connected, and to unlink those lines that did not exhibit continuous traffic flow, such as where an overpass bridge cut the link between two segments. Such circumstances were inspected and modified in the AutoCAD files.

Figure 3. A comparison of 3D historical maps from 2006 (right) and 2017 (left) provided by Google Earth Pro (source: Authors)

These maps were modified and simplified according to the methods of (Kolovou et al., 2017). The final maps for the twelve cases are shown in *Table 2*.

Table 2. Street maps of the twelve case areas, arranged by location category and density range

	Inner	Middle	Outer
Case A			
	Density: 271 p/ha	Density: 70 p/ha	Density: 27 p/ha
Case B			
	Density: 84 p/ha	Density: 81 p/ha	Density: 63 p/ha
Case C			
	Density: 226 p/ha	Density: 68 p/ha	Density: 46 p/ha
Case D			
	Density: 117 p/ha	Density: 59 p/ha	Density: 27 p/ha

3. ANALYSIS AND RESULTS

3.1 Spatial Analysis

Angular segment analysis was chosen for the space syntax analysis, as Hillier and Iida (2005) have shown that analysis based on angular distance is more representative of the actual pattern of the movement of people, given how they perceive the environment. That is, people tend to consider topological and geometric attributes when choosing the shortest path, rather than calculating the metric distance. Accordingly, because the cases varied in size, they were normalised to be comparable. As such, the normalised values using angular distance were Normalised Angular Choice (NACH), Normalised Angular Total Depth (NAtd) and Normalised Angular Integration (NAIN). The visual maps generated by the space syntax software, DepthMapX, are shown in *Table 1*. Along with visual maps, DepthMapX provides an Excel file generated from the calculation of the space syntax indices.

Before proceeding to the clustering with the eight cases explored in *Table 1*, all the twelve cases were categorised into one of three groups – low (27 p/ha), medium (60 – 70 p/ha) or high (< 200 p/ha) density – to explore general spatial features. The descriptive statistical analyses conducted to compare the mean space syntax values of the cases in this category were inspected using IBM SPSS Statistics (*Table 3*).

Table 3. Descriptive analysis of the mean and standard deviations of cases categorised by location and density range

CATEGORY		Connectivity	NAIN	NAtd	NACH
Inner	Mean	2.86	0.75	1.40	0.94
	Std. Deviation	1.04	0.18	0.49	0.32
Middle	Mean	2.67	0.82	1.31	0.98
	Std. Deviation	0.92	0.23	0.39	0.32
Outer	Mean	2.67	0.67	1.55	0.95
	Std. Deviation	0.90	0.14	0.36	0.31

Looking at the descriptive results when including cases with large differences in density categorised by location (*Table 3*), however, did not reveal any patterns regarding spatial design factors, as the cases did not follow any particular order across their categories. In contrast, studying the cases based on the clusters introduced in *Table 1* enabled us to control for density, revealing potential patterns in spatial design factors in a more accurate way.

Cluster 1: Two outer areas in Case A and Case D had the same net density of 27 p/ha. Case A's outer neighbourhood exhibited a compact super grid layout, whereas Case D had a curvilinear and cul-de-sac layout (*Figure 4*). The space syntax results for these neighbourhoods are shown in *Table 4*.

Table 4. Descriptive statistics for Cluster 1

Cluster 1		Connectivity	NAIN	NAtd	NACH	Layout
Case A	Mean	2.53	0.75	1.37	0.98	Compact Super grid
Case D	Mean	2.53	0.74	1.39	0.92	Curvilinear Cul-de-sac

Figure 4. The outer area of Case A above, and the outer area of Case C below

<u>*Cluster 2*</u>: This cluster included Case A's inner neighbourhood, with a 271 p/ha net density, and Case E's inner neighbourhood, with a net density of 226 p/ha. See *Figure 5* and *Table 5*.

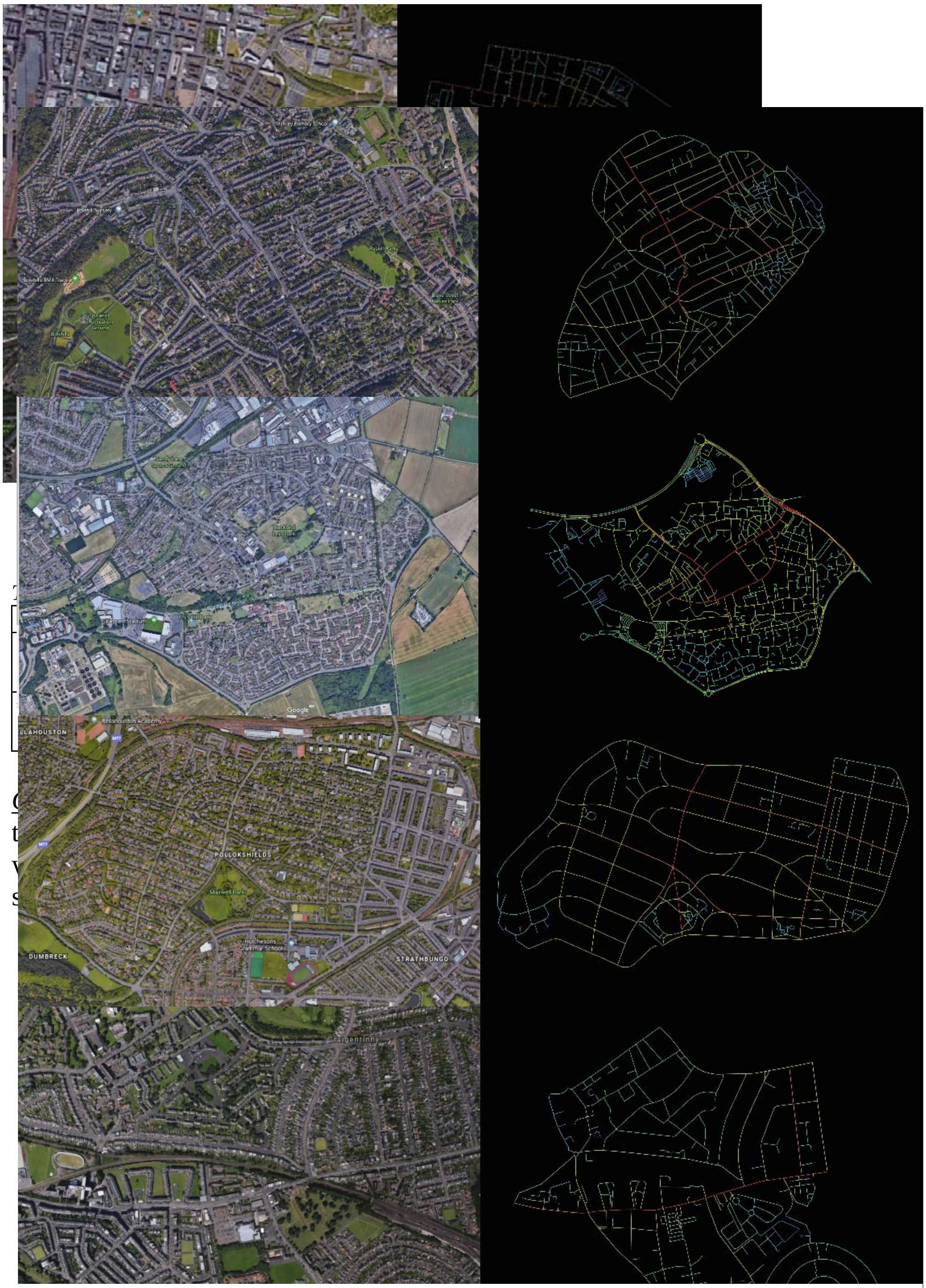

Figure 6. From top to bottom: the middle area of Case D, the outer area of Case B, the middle area of Case C, and the middle area of Case A.

Table 6. Descriptive statistics for Cluster 3

Cluster 3		Connectivity	NAIN	NAtd	NACH	Layout
Case D	Mean	2.70	0.77	1.32	0.92	Deformed compact grid
Case B	Mean	2.90	0.63	1.61	0.91	Cul-de-sac
Case C	Mean	2.82	1.08	0.98	1.04	Deformed compact grid
Case A	Mean	2.36	0.76	1.63	1.00	Grid

3.2 Statistical Analysis

The clusters enabled a better comparison of cases with the same/similar density. To explore differences among the three clusters representing low, medium and high density, the spatial data were compared using t-tests and one-way ANOVA tests. These tests were conducted to understand if there were meaningful differences in the mean of the spatial data of the three clusters. Although the results helped indicate meaningful differences, ANOVA and t-tests cannot specifically determine which case is affected or what causes that effect (Field, 2009). These methods have been employed in previous space syntax research as an important step to first confirm differences in mean values for comparison studies (Abshirini & Koch, 2017; Haq & Girotto, 2003).

An independent-samples t-test was undertaken to compare the spatial design factors, namely NACH, NAIN and NAtd, between the first two clusters representing low and high net density.

In Cluster 1, there was a significant difference in the scores for NAtd between the outer areas of Case A (M = 1.37) and Case D (M = 1.39); t(4568) = 2.20, p = 0.028. There was also a significant difference in NAIN values between Case A (M = 0.75) and Case D (M = 0.74); t(4568) = 2.24, p = 0.020. In contrast, there was no significant difference in NACH values between Case A (M = 0.98) and Case D (M = 0.92); t(4568) = 1.23, p = 0.215.

In Cluster 2, the independent-samples t-test showed that there was a significant difference in the scores for NAtd between Case A (M = 1.49) and Case C (M = 1.12); t(3080) = 27.42, p = 0.000. Tests of NAIN values also indicated a significant difference between Case A (M = 0.71) and Case C (M = 0.94); t(3080) = 32.70, p = 0.000. Similar to the previous cluster, however, the NACH values for Case A (M = 0.94) and Case C (M = 0.95) did not differ significantly; t(3080) = 0.41, p = 0.679.

In Cluster 3, a one-way ANOVA was undertaken to compare the same spatial design factors as the previous clusters. The results of the ANOVA showed significant differences among all four cases ($p < 0.05$) regarding NAtd, NAIN and NACH values. Post hoc testing was not conducted because differences among the cases within a cluster were not of interest for this paper. The results of the ANOVA are shown in *Table 7*.

Table 7. ANOVA results for Cluster 3

ANOVA						
		Sum of Squares	df	Mean Square	F	Sig.
NACH	Between Groups	2.029	2	1.01	27.47	.000

	Within Groups	222.85	6037	.037		
	Total	224.88	6039			
NAtd	Between Groups	126.22	2	63.11	883.92	.000
	Within Groups	431.04	6037	.071		
	Total	557.26	6039			
NAIN	Between Groups	90.05	2	45.029	1607.41	.000
	Within Groups	169.11	6037	.028		
	Total	259.17	6039			

4. DISCUSSION AND CONCLUSION

As the cases were clustered according to similar ranges of density, the results suggest that spatial design factors are different when comparing them against their relative density. This is especially the case when the layout forms of the cases also differ (*Figure 5*, *6* and *7*). The study did not find any design pattern based on the categories provided in *Table 3*, where cases were classified according to their density (p/ha) and location. In other words, when cases were compared across low, medium and high densities, the spatial design factors did not follow any particular order. Additionally, no pattern was found in the change of spatial design factors when categorising based on the location of the cases (*Table 3*), indicating that in these cases, spatial design was independent of location and density (p/ha). The refined clustering method (*Table 4*, *5* and *6*), however, made differences in the design pattern evident when cases with similar density ranges were compared, enabling statistical analysis to reveal the meaningful differences in most of the spatial design factors.

The outcomes emphasised that the same building density can yield different design layouts. They also demonstrated that the density measurement for this study, people per hectare (p/ha), which is normally used in census data and statistical studies, is not a proper representation of the design factors and does not give much information about specific configurational or morphological attributes.

As mentioned before, numerous design factors can be influential in defining density, including morphological characteristics of individual buildings, block types and design attributes of street networks. Moreover, many researchers agree that for density to be an effective measurement, it must integrate other aspects of the built environment, such as distribution of land-use, services and attraction points. Referring back to the literature, there is a lack of methodology for studying density in direct association with various design aspects of the built form (Grosvenor & O'NEILL, 2014). Furthermore, the existing methods that attempt to link design aspects to density usually miss exploring density in relation to spatial relationships and arrangements of the building and street networks, and merely focus on the mathematical measurements of the buildings and plots (Hamaina, Leduc, & Moreau, 2014). This can lead to ignoring the benefits that density can offer regarding the arrangement of streets and building form. In other words, the analysis should be more targeted to the way in which density makes some opportunities more accessible to residents, such as access to integral facilities, public transport, infrastructure, health services, etc. (Zainol &

Elsawa, 2018). Thus, focusing density measurements on the spatial network can help conduct a more in-depth analysis, which has become the focus of many novel spatial approaches such as place syntax analysis (Ståhle, Marcus, & Karlström, 2005) and urban network analysis (UNA) (Sevtsuk, Kalvo, & Ekmekci, 2016).

Considering the great potential of integrating other density-related aspects of urban built forms, such as the effect that density can have on people's movement behaviour, with spatial analysis, future studies could expand the application of such methods. This is possible due to the strong relationship that spatial network and space syntax studies have so far shown with social phenomena such as movement, co-presence, social interaction and safety (Matijosaitiene, 2016; Koohsari et al., 2019; Bendjedidi, Yassine, & Meziani, 2018). The development of integrated methodologies with innovative tools and approaches is important because understanding the various effects of intensifying urban areas is pivotal for effective and informative decision-making by planners and researchers. Future studies could also take a step forward and conduct in-depth statistical modelling to scrutinise the influence of various types of density on each of these spatial design factors when examining different built forms. Because the focus of this study was on spatial design factors, future developments of the topic could also include other aspects of the design of the built form, not only in relation to planar properties but also in three dimensions.

An enhancement of the method used here could be a more detailed classification of cases based on their specific layout designs and morphological typologies, where the study would have access to a more complete set of data. A limitation of this study was missing data concerning social aspects, such as movement patterns and transport behaviour, which could have been mapped through space syntax analysis. Future studies could dig deeper into the association of density with design and define that relationship in close relation to its potential impacts on people's daily life when social data are available. This integrated approach would enable a more meaningful analysis of the topic, not only referring to a number defining density but also considering various effects, risks and opportunities that could be created through different physical arrangements.

This research formed part of a PhD project that aims to explore the relationship of social sustainability and urban density in integration with design. In future steps, a computational design model will be developed to better understand the role of design in this trade-off. This will offer urban designers and planners a broader view of the possible effects of their decision-making regarding densifying urban areas.

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